

Performance study of an innovative natural gas CHP system

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ABSTRACT

In the last decade, technological innovation and changes in the economic and regulatory environment have resulted in increased attention to distributed energy systems (DES). Combined cooling heating and power (CHP) systems based on the gas-powered internal combustion engine (ICE) are increasingly used as small-scale distribution co-generators. This paper describes an innovative ICE–CHP system with an exhaust-gas-driven absorption heat pump (AHP) that has been set up at the energy-saving building in Beijing, China. The system is composed of an ICE, an exhaust-gas-driven AHP, and a flue gas condensation heat exchanger (CHE), which could recover both the sensible and latent heat of the flue gas. The steady performance and dynamic response of the innovative CHP system with different operation modes were tested. The results show that the system's energy utilization efficiency could reach above 90% based on lower heating value (LHV) of natural gas; that is, the innovative CHP system could increase the heat utilization efficiency 10% compared to conventional CHP systems, and the thermally activated components of the system have much more thermal inertia than the electricity generation component. The detailed test results provide important insight into CHP performance characteristics and could be valuable references for the control of CHP systems. The novel CHP system could take on a very important role in the CHP market.

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1. Introduction

Along with the development of distributed energy system (DES), the natural gas combined cooling, heating, and power (CHP) technology has also begun to be applied gradually. A typical CHP system consists of five basic elements: the prime mover; electricity generator; heat recovery system; thermally activated equipment and the management and control system. Different prime movers, connecting with different heat recovery equipments, can result in various kinds of CHP systems. A challenge for CHP system is the efficient integration of distributed generation (DG) equipment with thermally activated (TA) technologies [1]. Many research ministries and universities focus on assessing the operational performance and energy efficiency of the integration of current DG and TA technologies, and advance the technology and accelerate its application [2,3]. In all of these studies, experiment investigation is the most important way to study the critical issues of CHP system. One of the first CHP experiment applications is located at University of Maryland. Marantan et al. [4–6] integrated an absorption chiller and a liquid desiccant dehumidifier with two CHP systems driven by a micro-turbine and a gas engine. Sun [7] integrated a vapor compression chiller and a heat exchanger with a CHP system driven by a gas engine. In order to improve

the system performance, some studies [8–12] investigated the absorption chiller with the CHP system driven by the stirling engine, gas engine, or micro-turbine, and all of these studies pointed that the performance of CHP system could be improved by recovering waste heat. In China, CHP technology is still a promising energy conversion technology under development. Typical examples can be found at the Shanghai Huangpu Central Hospital, Pudong International Airport, the Beijing Gas Company building and Tsinghua University [13]. In all of these systems, the heat recovery units such as the waste heat boiler, the absorption chiller or the other devices are used to recover the waste heat of the prime mover, and the temperature of the flue gas exiting the system is always above 130 °C. The waste heat of the CHP system is much higher than that of a conventional gas boiler because the excess air coefficient of ICE or gas turbine is much higher than that of a conventional gas boiler. (The ICE's excess air coefficient is about 2, whereas the gas turbine's excess air coefficient is above 3.) If the flue gas temperature is 130 °C, the heat loss of the flue gas is always 25–30% in a CHP system, so the heat loss of the flue gas is still great, including the condensation heat. How to make use of this part of the heat is important, and it could be beneficial in saving energy and lowering costs. For the sake of full recovery of the condensation heat of the flue gas, an absorption heat pump (AHP) could be used. The conventional natural gas CHP system always has an absorption chiller, which could be altered to work as a heat pump to recover the waste heat of the flue gas including

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Nomenclature

AHP	absorption heat pump	LHV	lower heating value of natural gas
COP	coefficient of performance	NG	natural gas
CHE	condensation heat exchanger	ICE	internal combustion engine
CHP	cooling, heating, and power	TA	thermal activated
DAS	data acquisition system		
DES	distributed energy system		
DG	distributed generator		

the condensation heat. In this way, the energy utilization efficiency could be improved and the operation costs could be reduced, and the only increase in initial costs would be for the condensation heat exchanger. In order to study the performance of a cogeneration system with an AHP, a gas-powered internal combustion engine (ICE)-based cogeneration system has been designed and installed in a demonstration building at Tsinghua University. The system was used to match the base load of 3000 m² of cooling, thermal and electric demands. In the first part of this paper, the cogeneration system with an AHP is described. In the second part of the paper, the steady and dynamic performance of the system is analyzed. All the results provide important insights and valuable reference for CHP systems. Especially, in all of the experiment investigations in literature, there is not the dynamic performance of the CHP system reported, so the treatment of dynamic performance could be another significant contribution for the operation of the CHP systems.

2. Description of system

A natural gas CHP system has been set up at the Tsinghua University energy-saving building, in Beijing, China. The system is composed of a 70 kW_e gas-powered internal combustion engine (ICE), a 50 kW (cooling) exhaust-gas-driven absorption heat pump (AHP), a condensation heat exchanger (CHE), and other heat exchangers. The configuration of the system is shown in Fig. 1. The natural gas is used to fire the ICE, which generates power on-site. In the summer, the flue gas exiting the ICE is sent to the AHP to produce evaporator water, and the waste heat of the jacket water is used to drive the liquid desiccant machine, to realize the separate control of heat and humidity [15]. In the winter, the flue gas is used to drive the AHP, and the condensation heat of the flue gas is recovered in the CHE. The recovered heat is sent into the evaporator side of the AHP as a low-grade source. The heat produced by the condenser side of the AHP and the heat of the jacket water are combined together to satisfy the thermal load of the

building. In this study, we only focus on analyzing the performance in the winter mode.

In order to suppress the noise of the system, a muffler is mounted on the outlets of the exhaust pipeline, and a noise reduction method is adopted in the engine room. The main equipment of the system is the ICE and AHP. The ICE has six cylinders with four strokes, which is shown in Fig. 2, and the technical data of the 70 kW ICE is shown in Table 1.

The 50 kW double effects exhaust-gas-driven AHP is shown in Fig. 3, and the technical data is shown in Table 2.

A data acquisition system (DAS) was installed to measure all relevant temperatures, relative humidities, pressures, flow rates, and power consumption to calculate the performance of the CHP systems under all operating conditions. The main relevant parameters of the measurement instruments are shown in Table 3.

The DAS is completely separate from the control system, and the readings that the DAS records can be completely customized. The types of data the DAS can record are as follows: temperature, humidity, gas/air/exhaust/liquid flow rate, electricity, and current, pressure, equipment status, and weather station data. Most of the sensors output are 4–20 mA current, which has the advantage of avoiding signal attenuation over long wires. The current signal is converted into 0.88–4.4 VDC voltage, with which the required data value is calculated through the DAS program and then stored in the computer. The DAS user interface is shown in Fig. 4.

3. Performance of the innovative CHP system

3.1. Steady performance of the system

There are five temperature test points along the flue gas pipeline, mounted on the outlet of the ICE, the inlet and outlet of the AHP, and the inlet and outlet of the CHE. The temperature test points of the system are shown in Fig. 1. The test results for the five temperature points are expressed as T0–T4 and are illustrated in Fig. 5a. According to this figure, the temperature of the flue gas

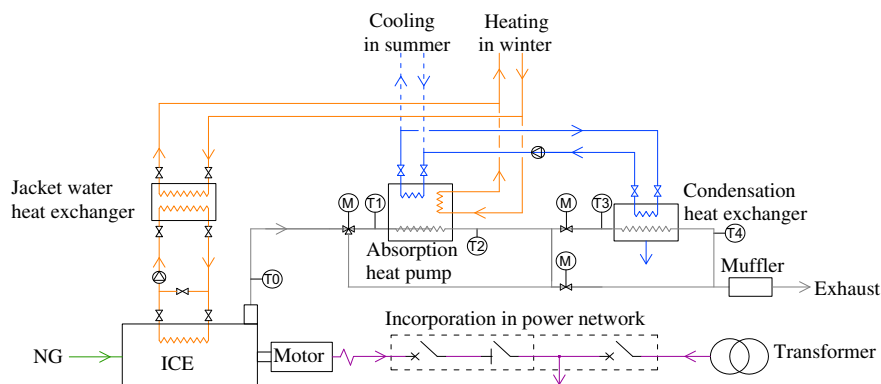


Fig. 1. Schematic of innovative CHP system in demonstration building.



Fig. 2. The 70 kW ICE.

Table 1

Technical data of the 70 kW ICE.

Subentry	Unit	Value
Rated electrical output	kW	70
Rated electrical voltage	V	400
Pressure of natural gas	bar	0.1–0.35
Rated flow of natural gas	m ³ /h	26.9
Exhaust temperature	°C	530
Excess air coefficient	–	1.1
Inlet temperature of jacket water	°C	82
Outlet temperature of jacket water	°C	98
Rated electrical efficiency (LHV)	%	27
Rated thermal efficiency (LHV)	%	38



Fig. 3. Double-effect exhaust-gas-driven absorption heat pump.

exiting the ICE (T_0) and the inlet temperature (T_1) of the AHP are about equal, as are the outlet temperature (T_2) of the AHP and the inlet temperature (T_3) of the CHE, indicating that the pipeline of the flue gas is well insulated. We also can see that the CHE could reduce the exhaust heat from 170 °C to 23 °C, so the system's outlet temperature could be reduced to 23 °C. The temperature profile of the water side is illustrated in Fig. 5b. The evaporator water of AHP recovers the flue gas condensation heat, and the condenser water is used to supply heat. The evaporator water temperature of the AHP is 17/20 °C, and the condenser water temperature is 45/41 °C.

The heat recovery of flue gas is shown in Fig. 5c. According to this illustration, the real heat recovery of the CHE accounts for

Table 2

Technical data of 50 kW AHP.

Subentry	Unit	Value
Cooling capacity	kW	50
Heating capacity	kW	46
Evaporator water outlet/inlet temperature	°C	18/21
Evaporator water flow rate	m ³ /h	14.3
Heating water outlet/inlet temperature	°C	54/50
Heating water flow rate	m ³ /h	10
Exhaust flow rate	m ³ /h	834 (530 °C)
Exhaust outlet/inlet temperature (cooling)	°C	160/530
The used heat of exhaust (cooling)	kW	45
Exhaust outlet/inlet temperature (heating)	°C	140/530
The used heat of exhaust (heating)	kW	47
Rated COP (cooling)	–	1.1
Maxim power consumption (cooling)	kW	4.8
Maxim power consumption (heating)	kW	1.6

Table 3

Relevant parameters of the measurement instruments.

Measurement parameter	Instrument	Measurement precision	Measurement periods/s
Natural gas flow rate	Natural gas flow meter	±1%	20
Electrical power	Electrical power meter	±1%	20
Water flow rate	Ultrasonic flow meter	±0.5%	20
Water temperature	T thermocouple	±0.5 °C	20
Exhaust temperature	K thermocouple	±0.5 °C	20

about 16% of the total input energy, and the heat recovery of the AHP accounts for about 30% of the total input energy. In the conventional CHP system, the flue gas–water heat exchanger always is used to recover the waste heat, and the heat recovery of flue gas–water heat exchanger accounts for about 20% of the total input energy [16], so compared with the conventional CHP system, the heat recovery of the novel system could be increased by 10%.

The efficiency distribution of the innovative system is shown in Fig. 5d. The electrical efficiency is defined as,

$$\eta_E = \frac{P_{out}}{Q_{inLHV}} \quad (1)$$

where P_{out} is power output of the ICE, Q_{inLHV} is the natural gas input energy (based on LHV).

The thermal recovery efficiency of jacket water is defined as,

$$\eta_{JW} = \frac{C_{pJW} \rho_{JW} \cdot G_{JW} \cdot (t_{JW_{in}} - t_{JW_{out}})}{Q_{inLHV}} \quad (2)$$

where C_{pJW} is the water heat capacity at the average temperature; ρ_{JW} is the density of water at the average temperature; G_{JW} is the volumetric flow rate of jacket water; and $t_{JW_{in}}$ and $t_{JW_{out}}$ are the jacket water temperatures entering and leaving the jacket water heat exchanger, respectively;

The thermal recovery efficiency of AHP is defined as,

$$\eta_{AHP} = \frac{C_{PAHP} \rho_{AHP} \cdot G_{AHP} \cdot (t_{AHP_{in}} - t_{AHP_{out}})}{Q_{inLHV}} \quad (3)$$

where C_{PAHP} is the heat capacity of the hot water flows from the condenser side of the AHP at the average temperature; ρ_{AHP} is the density of the hot water flows from the condenser side of the AHP at the average temperature; G_{AHP} is the volumetric flow rate of the water flows from the condenser side of the AHP; and $t_{AHP_{in}}$

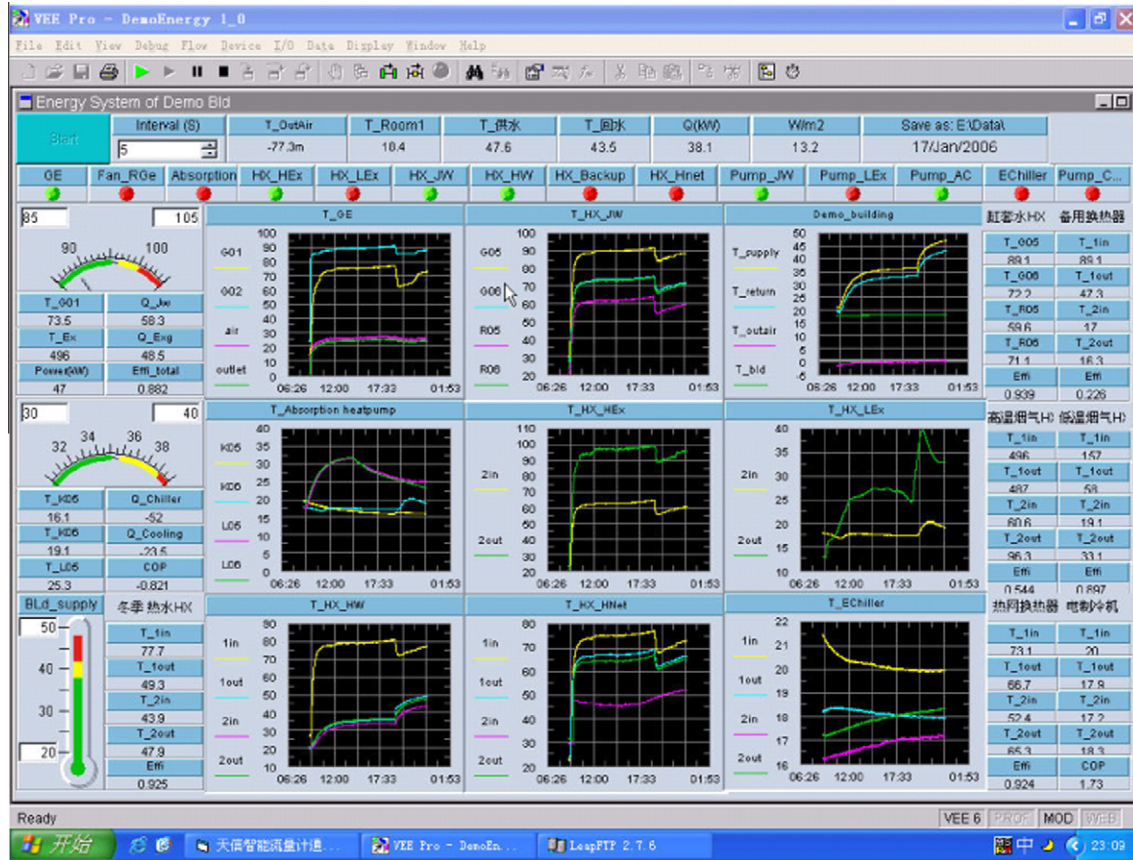


Fig. 4. The DAS user interface.

and $t_{AHP_{out}}$ are the water temperatures entering and leaving the condenser side of the AHP, respectively.

The system energy utilization efficiency is defined as,

$$\eta = \eta_E + \eta_{JW} + \eta_{AHP} \quad (4)$$

The output of the ICE is stabilized in a range from 59 kW to 60 kW at this time. The output heat of the AHP is about 70–72 kW t, and the recovery heat of the jacket water is about 87–89 kW t. The system's electrical efficiency is about 25%; the thermal recovery efficiency of the AHP is about 30–33%, and the thermal recovery efficiency of jacket water is about 36%, so the system's energy utilization efficiency is about 90–94% based on LHV of natural gas. It should be noted that the COP of the AHP is about 1.8–2.0, which is computed as useful thermal output of heat pump (condenser side)/energy input to the AHP.

All the steady test results of the system reflect the energy utilization level of the system.

3.2. Dynamic performance of the system

The question of how to operate the CHP system is important; the appropriate operation and modulation strategies could improve the system's overall performance, resulting in great economic benefits, so it is necessary to study the dynamic performance of the system.

The dynamic performance means the equipment output response speed and relative magnitude when the system is started or stopped, or the load is changed. The main equipment of the system includes the ICE and AHP, which are the main equipments of the system. The equipment's construction is complicated, and it has a great effect on the system. However, it is hard to build a dy-

namical model to simulate the system's dynamic response, so it had to be tested directly.

3.2.1. Dynamic performance of the ICE

In the design process of the CHP system for an office building, the ordinary operation strategies are shutdown in the evening, and start-up in the morning because the load of the building is much lower and the cost of electricity for the power grid is much lower at night than in the daytime. However, starting and stopping a system requires extra fuel; if the cost of fuel wasted is much higher than the cost saved between the hours the system is stopped and started, the operation will not save money. Furthermore, it is possible that the room temperature might fall below freezing at night, and the system's supply or return water could ice up. So there are three questions that must be answered. First, what does it cost to stop and start the system one time? Second, how does the indoor temperature change at night? Third, how long does it take for the ICE to recover its ability to heat effectively after it has been re-started? These questions could be answered by analysis of the ICE's stop and start performance.

The dynamic response of the ICE's start and stop cycle is illustrated in Fig. 6a and b. As shown in Fig. 6a, when the ICE is started, the engine turns over for about 1 min before successful connection to the grid. The electric power increases gradually after the system connects to the grid, and it is a typical vibrating modulation process before the electric power reaches the enactment power. After the grid connection has been achieved, it takes about another 3–5 min for stable power generation to begin.

When the ICE must be shut down, the power can be switched off suddenly, which may cause a concussion in the ICE. In order to prevent this concussion, the electric power must be decreased

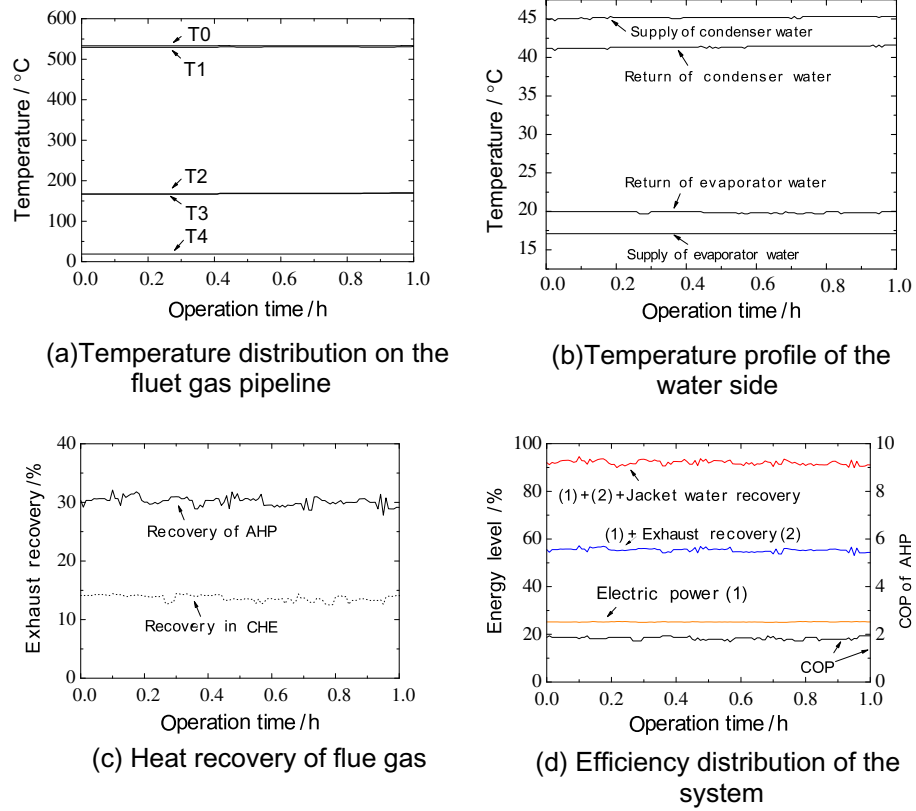


Fig. 5. The energy distribution status of different parts of the system.

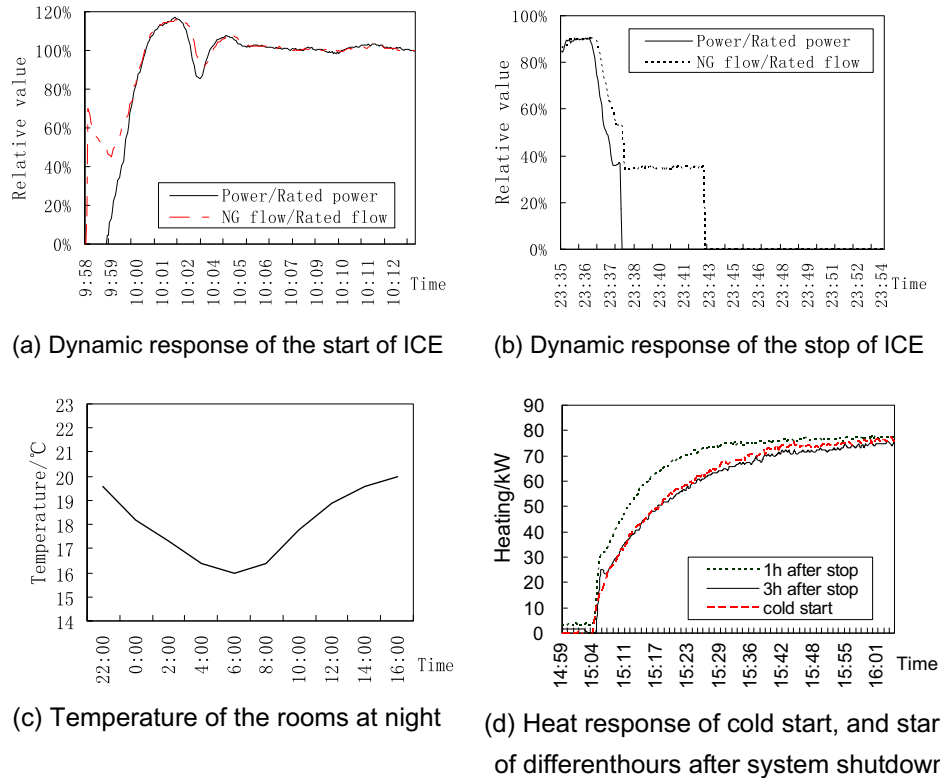


Fig. 6. Dynamic response of ICE.

gradually. As shown in Fig. 6b, this takes about 0.5–1 min. When the ICE is switched off, the flow of natural gas is still 35% of the rated flow in order to eliminate the remaining gas in the cylinder and vent-pipe, while the ICE runs for 5–6 min. Based on the switch-off process, we can see that the energy consumption costs of the ICE is about 35% of the rated flow, which takes 6 min, and about 1 m³ natural gas for the ICE.

The indoor air temperature is shown in Fig. 6c. The system was stopped at 22:00 pm, and started at 9:00 am, and the circulating pump of the heating system kept running during this time. As shown in Fig. 6c, the room temperature decreased 3–4 °C, and the rate of decrease was about 0.3–0.4 °C/h. The indoor air temperature was still above 15 °C 10 h after the system had been stopped. The system was not in danger of icing up, proving that it is feasible to stop the system at night.

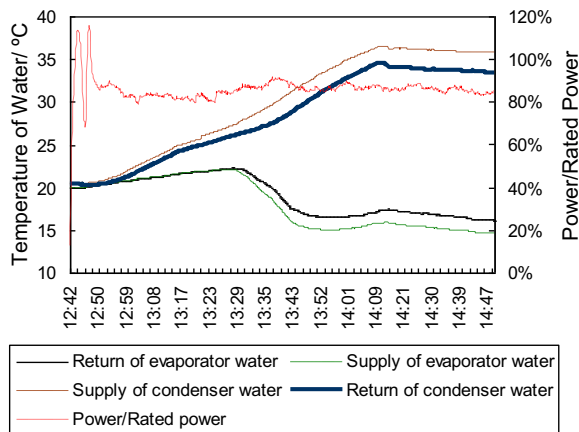
Fig. 6d shows the ICE's heat response for a cold start, and when started at different times after having been stopped. When the ICE is started 1 h after having been stopped, it takes 24 min to reach the rated heating ability. When it is started 3 h after being stopped, the ability to heat is recovered in 40 min, which is almost the same as the cold start. In other words, the system's ability to supply heat does not meet the building's requirements during the first 40 min after start-up. The strategy of stopping the system at night means the consumers' demands will not be met for about 40 min, which is acceptable for most typical consumers.

3.2.2. Dynamic performance of the AHP

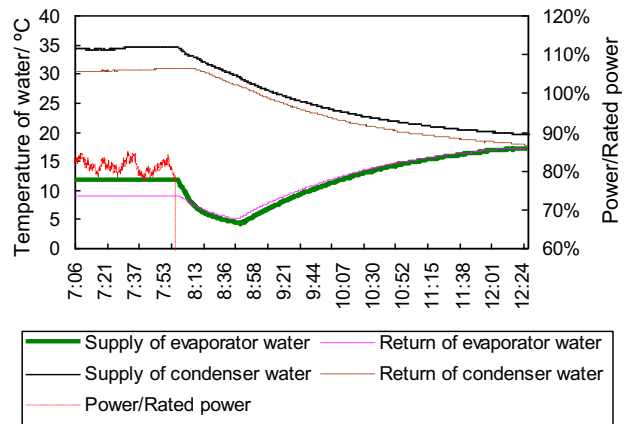
An exhaust-gas-driven AHP is used in the CHP system for the first time in China, and the secure control strategy is not predetermined, so the start and stop strategy should be studied through the dynamic performance of the AHP.

When the AHP is switched off, it means the flue gas valve before the high grade generator of the AHP is closed, and the air conditioning pump and the condenser water pump are turned off. At the same time, the AHP is in the condition of dilution. The dynamic response of the start of the AHP is shown in Fig. 7a. The AHP starts to provide cooling 45–50 min after it is started. The temperature of the evaporator water decreases gradually, and the temperature difference is increased gradually and stabilizes at a fixed temperature level. The temperature of the condenser water increases gradually, and the temperature difference is also increased gradually and stabilized at a fixed temperature level. The response speed of the condenser water is correlated with the thermal inertia of the building, which is higher than the thermal inertia of evaporator water. In the experimental system, the stabilization time of condenser water is 20–30 min later than that of the evaporator water.

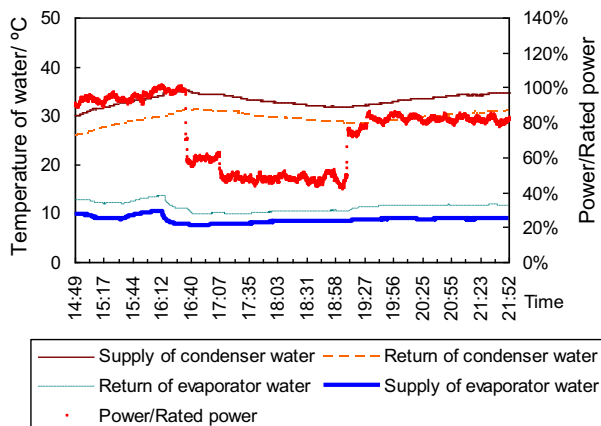
The dynamic response of the shutdown of the AHP is shown in Fig. 7b. The evaporator water temperature decreases gradually, and then increases until it is stabilized at a fixed temperature level. When the ICE and AHP are both switched off, the AHP still has the ability to cool, which results in a decline in the temperature of the



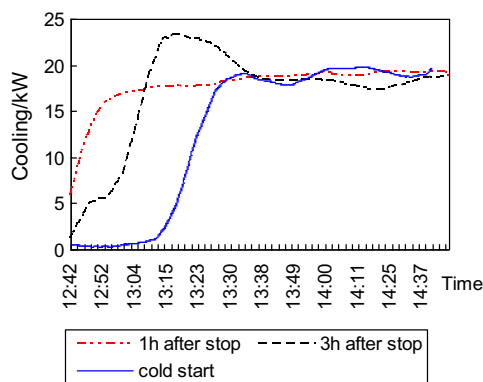
(a) Dynamic response of the start of AHP



(b) Dynamic response of the halt of AHP



(c) Dynamic response of load change of AHP



(d) Dynamic response of cold start, and start-up different hours after shutdown

Fig. 7. Dynamic response of AHP.

evaporator water until the remaining coolant is used, and then, the temperature of the evaporator water increases gradually until it reaches the desired temperature. As we can see, when the AHP is stopped, the evaporator water temperature decreases first, this may result in icing or the formation of crystals, so it is very important to stop the system properly in order to avoid crystallization.

The load change of the AHP is mainly realized by the load change of the ICE. The dynamic response of the load change is shown in Fig. 7c. When the load is changed, the response time of the evaporator water is about 10 min.

The AHP's dynamic response for a cold start-up and start-ups for different hours after the system has been stopped is depicted in Fig. 7d, which shows that the difference is great. The temperature of the high grade generator of the AHP is still 100 °C 1 h after the system has been stopped, and the AHP retains the ability to cool, so when it is started again, the cooling ability is recovered immediately. As for the cold start, the cooling ability can be recovered in 50 min.

As we can see, the thermal inertia of the AHP is higher than that of the ICE, so the operation log of the AHP has a great effect on its dynamic response. Through the measurement and analysis of different equipment's dynamic response, the system's thermally activated components, such as the AHP, have much more thermal inertia than the electricity generation component. The modulation period of the system is determined by the AHP, and may be longer than 50 min. So in the process of system modulation, the forecast of the exact load could be a guide for the system's modulation, which combined with the dynamic performance analyzed in the paper is an important reference for the control and modulation of the system. Additionally, the analysis of the dynamic performance presented in this paper also could be a reference for the start and stop sequences of different equipment.

4. Start and stop strategy of the innovative CHP system

In the novel system, the ICE, exhaust-gas-driven AHP and flue gas CHE are integrated for the first time. Which piece of equipment should be started first? And which should be second? Also, which should be stopped first, and which second? The start and stop strategy should be studied referring to the dynamic performance of the main equipment.

The system's start-up should follow a definite sequence. The ICE should be started first. It takes about 3–5 min for the ICE to stabilize power generation, so the AHP should be started 5 min later than the ICE. The CHE cannot be started at the same time as the AHP because it takes about 45–50 min for the AHP to begin cooling. In these 45–50 min, the solution of the AHP is preheated. If the AHP and CHE were started at the same time, the flue gas exiting the AHP would get into the CHE, which could cause the evaporator water to overheat.

The appropriate start sequence is as follows. First, the ICE is started and all the flue gas is bypassed to the exit. Five minutes later, the AHP is started, and 45–50 min later, the CHE is started.

The system's stop should also follow a definite sequence. There are two kinds of stop modes (Modes I and II) to choose from, depending on whether the ICE is stopped first or the AHP is stopped first. We carried out experiments to validate which is the best stop mode.

In Mode I, the ICE is stopped first. The AHP's drive source is cut, the evaporator in the AHP retains a large amount of refrigerant (water), which should be evaporated to dilute the solution, and the refrigerant pump continues to run. The CHE cannot be heated by the flue gas because the ICE has already been stopped. The capacity of the evaporator water side is relatively low, and the inertia of the evaporator water side is relatively small, so the evaporator water temperature decreases greatly. Two hours later, the

Table 4

Uncertainty of calculated results.

Parameter	Uncertainty (%)
ICE electrical efficiency	0.5
Jacket water thermal efficiency	2.2
System total thermal efficiency	6.1

evaporator water temperature decreases to 6 °C. At the same time, the evaporator in the AHP retains a large amount of refrigerant (water). If the refrigerant (water) were to evaporate further, the evaporator water temperature would become super-cooled, which would lead to icing. In Mode I, it takes about more than 2 h to stop the CHP system.

If the AHP is stopped first, the ICE is still running, and the flue gas of the ICE gets into the CHE. The evaporator water temperature increases, and the difference between the supply and return of evaporator water decreases. Twenty minutes later, the supply and return of evaporator water are about equal, which indicates that almost no refrigerant (water) is present in the evaporator of the AHP; that is, the AHP loses the ability to cool, so the ICE could be stopped. The evaporator water temperature decreases gradually and is stabilized at a higher temperature level, which would solve the problems of Mode I. In Mode II, it takes about 1.5 h to stop the CHP system. So Mode II is a much more secure shutdown scheme than Mode I.

5. Uncertainty analysis

This section describes the magnitude of uncertainty for the experimental results presented in this paper arising from uncertainties in the sensors used in the experimental set up. Table 3 shows the instrumentation used in the experimental work along with the associated error for each sensor.

The total uncertainty of a measurement due to the uncertainty of individual parameters is referred to as the propagation of uncertainty [14]. The total uncertainty of any function may be calculated as:

$$u_F = \sqrt{\left(\frac{\partial F}{\partial v_1} \times u_1\right)^2 + \left(\frac{\partial F}{\partial v_2} \times u_2\right)^2 + \cdots + \left(\frac{\partial F}{\partial v_n} \times u_n\right)^2} \quad (5)$$

where u_F is uncertainty of the function, u_n is uncertainty of the parameter, F is function, v_n is parameter of interest (measurement), n is number of variables.

Table 4 lists the total uncertainty for each characteristic parameter.

It was found that the calculated value of the electrical efficiency has an uncertainty of 0.5%. The uncertainty for the jacket water thermal efficiency calculation is 2.2% and the uncertainty for the total thermal efficiency calculation is 6.1%.

6. Conclusion

This paper describes an innovative CHP system with an exhaust-gas-driven AHP that was set up at the energy-saving building in Beijing, China. The system is composed of an ICE, an exhaust-gas-driven AHP, and a flue gas CHE, which could recover both the sensible and latent heat of the flue gas. The comprehensive performance of the innovative CHP system with different operation modes was tested. The main conclusions are as follows.

- It is feasible to use the flue gas condensation heat as the low-grade heat source for the AHP. It was shown that the electrical efficiency of the innovative system is about 25%, and the thermal recovery efficiency of the absorption heat pump is about 30–33%, while the thermal efficiency of the jacket water is about 36%. Thus, the system's energy utilization efficiency is

above 90% computed on the low heat value of natural gas. The innovative CHP system could increase heat utilization efficiency 10% compared with conventional CHP systems.

- The power generation ability of the ICE could be recovered in 6 min, and the heating ability could be recovered in 40 min. The cost of stopping the ICE one time is about 1 m³ natural gas. For this building, the operation strategy of turning the system off at night is feasible.
- The system's thermally activated components, such as the AHP, have much more thermal inertia than the electricity generation component. The modulation periods of the system are determined by the AHP, which may be longer than 50 min. Therefore, in the process of system modulation, the exact load forecast should be the guide for the system's modulation, which, combined with the dynamic performance analyzed in the paper, is an important reference for the control and modulation of the system.
- The appropriate start-up sequence for the system is as follows. The ICE should be started first, and all the flue gas should be bypassed to the exit. Five minutes later, the AHP should be started, and 45–50 min later, the CHE should be started. The appropriate sequence for turning the system off is as follows. First, the AHP is stopped, and then the ICE should be stopped when the supply and return of evaporator water are about equal.

The detailed test results provide important insights into CHP performance characteristics and could be valuable references for the control, modulation, start sequence, and stop sequence of CHP systems. The innovative CHP system could take on a very important role in the CHP market.

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